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RESEARCH MEMORANDUM

THEORETICAL PERFORMANCE OF LIQUID AMMONIA, HYDRAZINE AND MIXTURE OF LIQUID AMMONIA AND HYDRAZINE AS FUELS WITH LIQUID OXYGEN BIFLUORIDE AS OXIDANT FOR ROCKET ENGINES

II - HYDRAZINE

By Vearl N. Huff and Sanford Gordon

Lewis Flight Propulsion Laboratory
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THEORETICAL PERFORMANCE OF LIQUID AMMONIA, HYDRAZINE, AND MIXTURE OF LIQUID AMMONIA AND HYDRAZINE AS FUELS WITH LIQUID OXYGEN BIFLUORIDE AS OXIDANT FOR ROCKET ENGINES

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SUMMARY

Theoretical values of performance parameters for hydrazine with liquid oxygen bifluoride were calculated on the assumption of equilibrium composition during the expansion process for a wide range of fuel-oxidant and expansion ratios. Parameters included were specific impulse, combustion-chamber temperature, nozzle-exit temperature, equilibrium composition, mean molecular weight, characteristic velocity, coefficient of thrust, and ratio of nozzle-exit area to throat area.

The maximum value of specific impulse was 298.7 pound-seconds per pound for a chamber pressure of 300 pounds per square inch absolute (20.41 atm) and an exit pressure of 1 atmosphere. Additional calculations made to determine the effects of 5 percent of water in the hydrazine showed a decrease in performance of 2 to 5 specific-impulse units over the range of fuel-oxidant and expansion ratios presented.

INTRODUCTION

Hydrazine has been of interest for a number of years as a possible rocket fuel because of its high theoretical specific impulse with several oxidants. Extensive data exist in the literature on its availability, cost, and physical, chemical, and handling properties (reference 1).

Oxygen bifluoride is of interest as a rocket oxidant because its performance is better than that of oxygen, its handling and material problems may be simpler than those of fluorine, and its density is greater than either oxygen or fluorine. Additional information concerning oxygen bifluoride can be found in reference 2.

The performance of a mixture of ammonia and hydrazine with oxygen bifluoride was reported in part I of this series (reference 3). The

performance of hydrazine with oxygen bifluoride has been reported in the literature. To determine a larger number of performance parameters over a wider range of conditions than previously published and to determine the effect of a small amount of water in the hydrazine, additional calculations were made at the NACA Lewis laboratory.

Data were calculated on the basis of equilibrium composition during expansion and cover a wide range of fuel-oxidant and expansion ratios. The performance parameters included are specific impulse, combustion-chamber temperature, nozzle-exit temperature, equilibrium composition, mean molecular weight, characteristic velocity, coefficient of thrust, and ratio of nozzle-exit area to throat area.

SYMBOLS

The following symbols are used in this report:

A	number of equivalent formulas (function of pressure and molecular weight; see reference 4)
A_e/A_t	ratio of nozzle-exit area to throat area
a	local velocity of sound, ft/sec
C_F	coefficient of thrust
c_p/c_v	ratio of specific heats
c^*	characteristic velocity, ft/sec
D_A	$\left(\frac{\partial \log A}{\partial \log T}\right)_s$
D_i	$\left(\frac{\partial \log p_i}{\partial \log T}\right)_s$
$f_1, f_2, \ldots f_5$	functions
h	enthalpy, including both sensible and chemical energy per unit weight, cal/g
I	specific impulse, lb-sec/lb
M	mean molecular weight, g/mole
n	number of atoms

P pressure

p_i partial pressure of a product of combustion

R gas constant (consistent units)

r equivalence ratio, ratio of number of hydrogen atoms to sum of number of fluorine atoms plus two times number of oxygen atoms in propellant, $\dfrac{n_H}{n_F + 2n_O}$

T temperature, $^{\circ}K$

γ_s $\left(\dfrac{\partial \log P}{\partial \log \rho}\right)_s$

ρ density

Subscripts:

c combustion chamber

e nozzle exit

max maximum

o conditions at 0° K, assuming recombination is complete

s constant entropy

METHOD OF CALCULATION

Calculations were made with an IBM Card Programmed Electronic Calculator as described in reference 3. The set of assumptions, products of combustion, and thermodynamic data used for the calculations are the same as those of reference 3. The dissociation of energy of F_2 was taken to be 35.6 kilocalories per mole (reference 5).

Composition of fuels. - Performance calculations were made for two fuels with oxygen bifluoride as the oxidant. One fuel was hydrazine containing no water, which will be designated pure fuel, and the other was hydrazine containing 5 percent water by weight, which will be designated commercial fuel. It was assumed that the water would combine with hydrazine to form hydrazine hydrate, resulting in a composition for commercial fuel of 1 mole hydrazine to 0.1033 mole hydrazine hydrate.

Procedure for combustion conditions. - The values of temperature, entropy, equilibrium composition and mean molecular weight of the products of combustion corresponding to an adiabatic combustion process were obtained for eight equivalence ratios as described in reference 3.

Procedure for exit conditions. - Equilibrium composition, mean molecular weight, pressure, derivative of the logarithm of pressure with respect to the logarithm of density at constant entropy γ_s, and enthalpy of the products of combustion were computed for each equivalence ratio by assuming isentropic expansion for six assigned exit temperatures for pure fuel and five assigned exit temperatures for commercial fuel covering the exit pressure range from the nozzle-throat pressure to about 0.02 atmosphere.

The function

$$\left(\frac{\partial \log P}{\partial \log \rho}\right)_s = \gamma_s$$

was used in the computation of throat conditions, since

$$a^2 = \left(\frac{\partial P}{\partial \rho}\right)_s = \left(\frac{\partial \log P}{\partial \log \rho}\right)_s \frac{P}{\rho} = \gamma_s R\frac{T}{M}$$

The derivative γ_s is equal to the ratio of specific heats c_p/c_v only when the molecular weight is constant. In the nomenclature of reference 4,

$$\gamma_s = \frac{\sum p_i D_i}{D_A - 1}$$

where

$$D_i = \left(\frac{\partial \log p_i}{\partial \log T}\right)_s$$

and

$$D_A = \left(\frac{\partial \log A}{\partial \log T}\right)_s$$

The numerical values of D_i and D_A were computed by the method given in reference 4 and were used to calculate the value of γ_s.

Interpolation formulas. - Temperature, composition, and entropy for combustion conditions were obtained by the same interpolation formulas described in reference 3.

Throat parameters and exit parameters corresponding to altitudes of 0, 20,000, 40,000, 60,000, and 80,000 feet were interpolated by means of cubic equations between each pair of the assigned exit temperatures. The coefficients of the cubic equations were determined from the values of the following functions and their first derivatives at each pair of the assigned temperatures:

$$f_1 = \ln\left(\frac{h}{R} + \frac{\gamma_s T}{2M} - \frac{h_o}{R}\right)$$

$$f_2 = \frac{h}{R}$$

$$f_3 = \ln T$$

$$f_4 = \ln M$$

$$f_5 = \ln P$$

$$\frac{df_1}{df_5} = \frac{T}{2Mf_1}\left(\gamma_s + 1 + \frac{d\gamma_s}{df_5}\right)$$

$$\frac{df_2}{df_5} = \frac{T}{M}$$

$$\frac{df_3}{df_5} = \frac{1}{\gamma_s\ (D_A - 1)}$$

$$\frac{df_4}{df_5} = \frac{D_A}{\gamma_s\ (D_A - 1)} - 1$$

(The value of $\frac{d\gamma_s}{df_5}$ was found by a numerical method.)

The pressure at the throat was found by interpolating f_5 as a function of f_1 for the point $f_1 = \log\left(\frac{h_c}{R} - \frac{h_o}{R}\right)$, at which the velocity of flow equals the velocity of sound. The values of the remaining functions were interpolated as functions of f_5 for the desired pressures.

The errors due to interpolation were checked for several cases. The values presented for all performance parameters appear to be correctly interpolated to one or two units in the last place tabulated.

THEORETICAL PERFORMANCE

The calculated values of the various performance parameters for both propellants (pure fuel and commercial fuel) for a combustion pressure of 300 pounds per square inch absolute and at exit pressures corresponding to altitudes of 0, 20,000, 40,000, 60,000, and 80,000 feet are given in tables I and II for eight equivalence ratios. The values of pressure corresponding to the assigned altitudes were taken from references 6 and 7. Equilibrium composition in the combustion chamber and equilibrium composition and γ_s at assigned exit temperatures are given in tables III and IV.

The parameters for both propellants are plotted in figures 1 to 6. Curves of specific impulse for the five altitudes are plotted against weight-percent fuel in figure 1. The difference between the curves for pure and commercial fuels for any altitude is about 2 to 5 impulse units over the entire range of weight-percent fuel presented. For pure fuel the maximum value of specific impulse for the sea-level curve is 298.7 pound-seconds per pound at 43.1 percent of fuel by weight; whereas for commercial fuel the maximum is 295.6 pound-seconds per pound at 43.6 percent of fuel by weight.

The maximum values of specific impulse and the values of weight-percent fuel at which they occur are plotted in figure 2 as functions of altitude. The maximum specific impulse increases 32.1 percent for both fuels for a change in altitude from sea level to 80,000 feet.

Curves of combustion-chamber temperature and nozzle-exit temperature for the five altitudes are presented in figure 3 as functions of weight-percent fuel. The maximum combustion temperature occurs at the extreme oxidant-rich end of the curves, being 3957° K at 22.9 percent fuel by weight for pure fuel and 3921° K at 23.4 percent fuel by weight for commercial fuel. The maximums of the exit-temperature curves occur near the stoichiometric mixture.

Characteristic velocity and coefficient of thrust are plotted in figure 4 and ratios of the area at the nozzle exit to area at the throat are shown in figure 5 as functions of weight-percent fuel.

Curves of mean molecular weight in the combustion chamber and in the nozzle exit are plotted against weight-percent fuel in figure 6.

Values of the parameters c^*, C_F, and A_e/A_t for a constant expansion ratio are only slight functions of chamber pressure and may be used at other pressures with small error.

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TABLE I - CALCULATED PERFORMANCE OF 100 PERCENT HYDRAZINE WITH OXYGEN BIFLUORIDE

[Pure fuel; combustion-chamber pressure, 300 lb/sq in. abs]

Propellant			Combustion chamber		Characteristic velocity	Nozzle exit						
Equivalence ratio r	Weight-percent fuel	Density[a] (g/cc)	Temperature T_c (°K)	Mean molecular weight M_c	c^* (ft/sec)	Altitude (ft)	Pressure P (atm)	Temperature T_e (°K)	Mean molecular weight M_e	Ratio of nozzle-exit area to throat area A_e/A_t	Coefficient of thrust C_F	Specific impulse I (lb-sec/lb)
0.5	22.88	1.511	3957	21.26	6383	0	1.0	2846	22.85	3.916	1.426	282.9
						20,000	.4594	2562	23.11	6.932	1.561	309.6
						40,000	.1852	2198	23.28	13.55	1.687	334.7
						60,000	.07125	1796	23.34	27.05	1.790	355.2
						80,000	.02780	1432	23.34	52.97	1.868	370.6
0.75	30.80	1.438	3932	19.90	6576	0	1.0	2872	21.58	3.941	1.427	291.6
						20,000	.4594	2620	21.90	7.041	1.563	319.4
						40,000	.1852	2305	22.16	14.02	1.692	345.9
						60,000	.07125	1937	22.28	28.63	1.800	368.0
						80,000	.02780	1576	22.29	57.04	1.884	385.0
1.0	37.24	1.383	3847	18.88	6682	0	1.0	2848	20.53	3.973	1.429	296.7
						20,000	.4594	2622	20.88	7.143	1.566	325.3
						40,000	.1852	2351	21.20	14.43	1.698	352.6
						60,000	.07125	2039	21.41	30.20	1.810	376.0
						80,000	.02780	1706	21.50	61.50	1.899	394.5
1.25	42.59	1.341	3747	18.07	6740	0	1.0	2702	19.49	3.911	1.426	298.7
						20,000	.4594	2414	19.69	6.880	1.560	326.8
						40,000	.1852	2040	19.78	13.29	1.685	352.9
						60,000	.07125	1661	19.80	26.56	1.786	374.1
						80,000	.02780	1336	19.80	52.39	1.863	390.2
1.50	47.10	1.308	3632	17.39	6749	0	1.0	2456	18.46	3.762	1.419	297.6
						20,000	.4594	2121	18.54	6.462	1.546	324.4
						40,000	.1852	1745	18.56	12.25	1.662	348.7
						60,000	.07125	1400	18.56	24.19	1.755	368.1
						80,000	.02780	1114	18.56	47.46	1.825	382.7
1.75	50.95	1.280	3506	16.81	6720	0	1.0	2222	17.58	3.623	1.411	294.7
						20,000	.4594	1885	17.61	6.149	1.533	320.2
						40,000	.1852	1533	17.61	11.57	1.643	343.1
						60,000	.07125	1219	17.61	22.70	1.730	361.4
						80,000	.02780	962	17.61	44.28	1.795	375.0
2.0	54.27	1.258	3376	16.32	6667	0	1.0	2025	16.86	3.514	1.404	291.0
						20,000	.4594	1701	16.87	5.926	1.522	315.5
						40,000	.1852	1373	16.87	11.10	1.628	337.3
						60,000	.07125	1085	16.87	21.67	1.711	354.6
						80,000	.02780	851	16.87	42.07	1.774	367.5
2.5	59.74	1.222	3125	15.51	6525	0	1.0	1729	15.78	3.371	1.395	282.9
						20,000	.4594	1438	15.78	5.647	1.508	305.8
						40,000	.1852	1150	15.78	10.50	1.608	326.1
						60,000	.07125	899	15.78	20.35	1.687	342.1
						80,000	.02780	700	15.78	39.23	1.745	353.9

[a]Based on OF_2 density of 1.77 at -195.8° C.

TABLE II - CALCULATED PERFORMANCE OF 86.11 PERCENT HYDRAZINE AND 13.89 PERCENT HYDRAZINE HYDRATE BY WEIGHT WITH OXYGEN BIFLUORIDE

[Commercial fuel; combustion-chamber pressure, 300 lb/sq in. abs]

Propellant			Combustion chamber		Character-istic velocity c^* (ft/sec)	Nozzle exit						
Equiv-alence ratio r	Weight-percent fuel	Density[a] (g/cc)	Temper-ature T_c ($^\circ$K)	Mean molec-ular weight M_c		Altitude (ft)	Pressure P (atm)	Temper-ature T_e ($^\circ$K)	Mean molecular weight M_e	Ratio of nozzle-exit area to throat area A_e/A_t	Coeffi-cient of thrust C_F	Specific impulse I (lb-sec/lb)
0.5	23.38	1.507	3921	21.33	6345	0	1.0	2810	22.88	3.908	1.426	281.2
						20,000	.4594	2520	23.13	6.900	1.560	307.6
						40,000	.1852	2147	23.28	13.41	1.685	332.3
						60,000	.07125	1742	23.32	26.61	1.787	352.5
						80,000	.02780	1385	23.32	52.01	1.864	367.5
0.75	31.65	1.432	3879	19.97	6521	0	1.0	2826	21.61	3.938	1.427	289.2
						20,000	.4594	2571	21.91	7.023	1.563	316.7
						40,000	.1852	2247	22.14	13.92	1.691	342.8
						60,000	.07125	1875	22.23	28.28	1.799	364.5
						80,000	.02780	1523	22.24	56.28	1.880	381.1
1.0	38.45	1.375	3789	18.94	6623	0	1.0	2801	20.55	3.973	1.429	294.1
						20,000	.4594	2574	20.88	7.135	1.566	322.4
						40,000	.1852	2296	21.18	14.36	1.698	349.5
						60,000	.07125	1976	21.36	29.89	1.809	372.5
						80,000	.02780	1645	21.42	60.66	1.897	390.5
1.25	44.14	1.331	3681	18.11	6673	0	1.0	2627	19.45	3.890	1.425	295.6
						20,000	.4594	2324	19.60	6.795	1.558	323.2
						40,000	.1852	1949	19.67	13.06	1.681	348.6
						60,000	.07125	1583	19.68	26.01	1.780	369.2
						80,000	.02780	1270	19.68	51.35	1.855	384.8
1.50	48.97	1.296	3551	17.40	6667	0	1.0	2346	18.34	3.712	1.416	293.5
						20,000	.4594	2010	18.39	6.342	1.542	319.5
						40,000	.1852	1647	18.40	12.00	1.655	343.0
						60,000	.07125	1319	18.40	23.68	1.746	361.8
						80,000	.02780	1048	18.40	46.42	1.814	375.9
1.75	53.12	1.268	3404	16.79	6616	0	1.0	2092	17.41	3.563	1.407	289.4
						20,000	.4594	1766	17.42	6.030	1.527	314.0
						40,000	.1852	1432	17.42	11.33	1.635	336.1
						60,000	.07125	1136	17.42	22.21	1.720	353.7
						80,000	.02780	896	17.42	43.27	1.784	366.8
2.0	56.72	1.244	3249	16.26	6536	0	1.0	1884	16.66	3.455	1.400	284.4
						20,000	.4594	1578	16.66	5.818	1.516	308.0
						40,000	.1852	1271	16.66	10.88	1.620	329.0
						60,000	.07125	1002	16.66	21.22	1.702	345.6
						80,000	.02780	785	16.66	41.13	1.762	358.0
2.5	62.68	1.206	2947	15.37	6335	0	1.0	1579	15.53	3.324	1.392	274.1
						20,000	.4594	1310	15.53	5.560	1.503	296.0
						40,000	.1852	1044	15.53	10.32	1.602	315.4
						60,000	.07125	815	15.53	19.96	1.679	330.7
						80,000	.02780	633	15.53	38.41	1.737	341.9

[a] Based on OF_2 density of 1.77 at -195.8° C.

TABLE III - EQUILIBRIUM COMPOSITION IN COMBUSTION CHAMBER AND FOLLOWING AN ISENTROPIC EXPANSION TO ASSIGNED EXIT TEMPERATURES

[Pure fuel: 100 percent N_2H_4; oxidant: OF_2]

Temperature T (°K)	Pressure P (atm)	γ_s $\left(\frac{\partial \log P}{\partial \log \rho}\right)_S$	Equilibrium composition (mole fraction)										
			HF	H_2	H_2O	OH	O_2	NO	N_2	F	H	O	N
					r = 0.50 (22.88 percent fuel by weight)								
3957	20.41	------	0.53196	0.00422	0.00943	0.02692	0.07560	0.02922	0.13523	0.07537	0.02116	0.08690	0.00399
3800	13.87	1.1528	.54756	.00341	.00911	.02421	.08297	.02767	.13814	.06650	.01725	.08010	.00307
3400	4.813	1.1506	.58671	.00171	.00786	.01674	.10462	.02288	.14572	.04466	.00878	.05896	.00136
2900	1.166	1.1620	.62946	.00044	.00536	.00763	.13420	.01544	.15486	.02146	.00223	.02862	.00030
2500	.3906	1.1974	.65244	.00007	.00292	.00254	.15311	.00923	.16069	.00986	.00034	.00975	.00005
2000	.1158	1.2738	.66445	-------	.00069	.00023	.16399	.00326	.16489	.00162	.00001	.00087	-------
1400	.02539	1.3331	.66662	-------	.00002	-------	.16649	.00032	.16651	.00004	-------	-------	-------
					r = 0.75 (30.80 percent fuel by weight)								
3932	20.41	------	0.48675	0.03262	0.05272	0.05114	0.03576	0.02266	0.17775	0.02315	0.05627	0.05691	0.00426
3800	14.69	1.1545	.49564	.03091	.05761	.04943	.03814	.02145	.18071	.01943	.05049	.05277	.00342
3300	3.717	1.1487	.52716	.02265	.08152	.03963	.04798	.01617	.19220	.00853	.02840	.03456	.00119
2900	1.093	1.1521	.54848	.01387	.10554	.02767	.05613	.01138	.20111	.00344	.01290	.01912	.00035
2500	.3210	1.1773	.56336	.00539	.12747	.01417	.06342	.00676	.20822	.00098	.00325	.00692	.00006
2200	.1398	1.2191	.56893	.00162	.13740	.00620	.06753	.00389	.21150	.00026	.00061	.00204	.00001
1500	.02245	1.3051	.57140	.00001	.14277	.00015	.07119	.00040	.21408	-------	-------	.00001	-------
					r = 1.00 (37.24 percent fuel by weight)								
3847	20.41	------	0.42808	0.07232	0.09206	0.04910	0.01564	0.01533	0.20993	0.01070	0.07161	0.03163	0.00360
3700	13.91	1.1516	.43546	.06956	.10162	.04642	.01593	.01397	.21365	.00859	.06386	.02816	.00278
3200	3.214	1.1435	.45997	.05589	.14210	.03385	.01547	.00900	.22672	.00339	.03692	.01578	.00092
2800	.8482	1.1446	.47782	.03936	.18157	.02078	.01251	.00510	.23683	.00119	.01757	.00702	.00025
2400	.2174	1.1654	.49136	.02013	.21913	.00853	.00720	.00206	.24476	.00026	.00483	.00170	.00004
2100	.08520	1.2036	.49702	.00850	.23816	.00281	.00327	.00073	.24817	.00005	.00098	.00030	-------
1700	.02733	1.2658	.49963	.00129	.24838	.00026	.00054	.00009	.24977	-------	.00003	.00001	-------
					r = 1.25 (42.59 percent fuel by weight)								
3747	20.41	------	0.37865	0.11776	0.11638	0.03803	0.00613	0.00940	0.23399	0.00549	0.07538	0.01600	0.00280
3600	13.86	1.1526	.38437	.11583	.12698	.03453	.00567	.00811	.23778	.00425	.06703	.01336	.00211
3000	2.421	1.1533	.40602	.10584	.17513	.01675	.00242	.00300	.25268	.00102	.03290	.00380	.00044
2700	.9939	1.1716	.41405	.10257	.19527	.00803	.00081	.00117	.25833	.00033	.01819	.00110	.00014
2400	.4439	1.2105	.41866	.10281	.20621	.00248	.00012	.00027	.26156	.00007	.00763	.00015	.00003
1900	.1317	1.2734	.42088	.10492	.21034	.00010	-------	.00001	.26305	-------	.00071	-------	-------
1300	.02480	1.3125	.42105	.10526	.21053	-------	-------	-------	.26316	-------	-------	-------	-------

TABLE III - EQUILIBRIUM COMPOSITION IN COMBUSTION CHAMBER AND FOLLOWING AN ISENTROPIC EXPANSION TO ASSIGNED EXIT

TEMPERATURES - Concluded

[Pure fuel: 100 percent N_2H_4; oxidant: OF_2]

Temperature T (°F)	Pressure P (atm)	γ_s $\left(\frac{\partial \log P}{\partial \log \rho}\right)_S$	Equilibrium composition (mole fraction)										
			HF	H_2	H_2O	OH	O_2	NO	N_2	F	H	O	N
r = 1.50 (47.10 percent fuel by weight)													
3632	20.41	------	0.33788	0.16638	0.12740	0.02595	0.00218	0.00531	0.25190	0.00285	0.07082	0.00735	0.00199
3500	14.60	1.1596	.34170	.16667	.13556	.02262	.00181	.00436	.25498	.00218	.06285	.00577	.00149
2900	2.998	1.1773	.35615	.17116	.16809	.00757	.00034	.00102	.26677	.00038	.02737	.00090	.00025
2500	1.108	1.2157	.36133	.17697	.17850	.00186	.00003	.00018	.27093	.00006	.01002	.00009	.00004
2100	.4371	1.2614	.36323	.18074	.18139	.00021	-------	.00001	.27242	-------	.00200	-------	-------
1500	.09569	1.3044	.36363	.18180	.18182	-------	-------	-------	.27272	-------	.00002	-------	-------
1100	.02642	1.3306	.36364	.18182	.18182	-------	-------	-------	.27273	-------	-------	-------	-------
r = 1.75 (50.95 percent fuel by weight)													
3506	20.41	------	0.30400	0.21484	0.12901	0.01630	0.00073	0.00283	0.26522	0.00147	0.06114	0.00314	0.00132
3300	12.42	1.1723	.30822	.21858	.13818	.01183	.00044	.00184	.26916	.00088	.04828	.00182	.00077
2900	4.715	1.1910	.31467	.22724	.15157	.00473	.00010	.00056	.27516	.00024	.02515	.00039	.00020
2400	1.489	1.2374	.31884	.23641	.15867	.00069	-------	.00005	.27897	.00002	.00632	.00002	.00001
1900	.4761	1.2835	.31991	.23966	.15993	.00003	-------	-------	.27992	-------	.00056	-------	-------
1300	.09288	1.3199	.32000	.24000	.16000	-------	-------	-------	.28000	-------	-------	-------	-------
900	.02144	1.3496	.32000	.24000	.16000	-------	-------	-------	.28000	-------	-------	-------	-------
r = 2.00 (54.27 percent fuel by weight)													
3376	20.41	------	0.27561	0.26003	0.12520	0.00976	0.00024	0.00147	0.27522	0.00075	0.04962	0.00128	0.00082
3200	13.67	1.1850	.27819	.26478	.13047	.00692	.00014	.00094	.27793	.00046	.03896	.00072	.00049
2700	4.427	1.2165	.28332	.27741	.13979	.00166	.00001	.00015	.28328	.00007	.01418	.00007	.00007
2100	1.186	1.2721	.28548	.28477	.14266	.00008	-------	-------	.28548	-------	.00152	-------	-------
1700	.4580	1.2992	.28570	.28564	.14285	-------	-------	-------	.28570	-------	.00012	-------	-------
1200	.1067	1.3292	.28571	.28571	.14286	-------	-------	-------	.28571	-------	-------	-------	-------
800	.02195	1.3599	.28571	.28571	.14286	-------	-------	-------	.28571	-------	-------	-------	-------
r = 2.50 (59.74 percent fuel by weight)													
3125	20.41	------	0.23113	0.33484	0.11171	0.00330	0.00003	0.00039	0.28882	0.00020	0.02908	0.00021	0.00029
2900	12.76	1.2152	.23273	.34106	.11437	.00177	.00001	.00018	.29087	.00009	.01872	.00007	.00012
2400	4.506	1.2549	.23473	.35004	.11711	.00024	-------	.00002	.29341	.00001	.00442	-------	.00001
1800	1.191	1.2980	.23527	.35281	.11763	-------	-------	-------	.29409	-------	.00019	-------	-------
1300	.3034	1.3265	.23529	.35294	.11765	-------	-------	-------	.29412	-------	-------	-------	-------
1000	.1071	1.3476	.23529	.35294	.11765	-------	-------	-------	.29412	-------	-------	-------	-------
700	.02781	1.3705	.23529	.35294	.11765	-------	-------	-------	.29412	-------	-------	-------	-------

TABLE IV - EQUILIBRIUM COMPOSITION IN COMBUSTION CHAMBER AND FOLLOWING AN ISENTROPIC EXPANSION TO ASSIGNED EXIT TEMPERATURES

[Commercial fuel: 86.11 percent N_2H_4 and 13.89 percent $N_2H_4 \cdot H_2O$ by weight; oxidant: OF_2]

Temperature T (°K)	Pressure P (atm)	γ_s $\left(\frac{\partial \log P}{\partial \log \rho}\right)_S$	Equilibrium composition (mole fraction)										
			HF	H_2	H_2O	OH	O_2	NO	N_2	F	H	O	N
r = 0.50 (23.38 percent fuel by weight)													
3921	20.41	------	0.53839	0.00450	0.01125	0.02861	0.08163	0.02921	0.13145	0.06679	0.02051	0.08410	0.00355
3900	19.39	1.1543	.54048	.00439	.01122	.02825	.08262	.02900	.13184	.06559	.01998	.08319	.00343
3600	9.046	1.1513	.56972	.00292	.01075	.02278	.09786	.02561	.13737	.04912	.01317	.06872	.00198
2900	1.288	1.1631	.63008	.00068	.00882	.00962	.13827	.01543	.15008	.01646	.00263	.02764	.00028
2300	.2657	1.2304	.65697	.00008	.00744	.00227	.16220	.00645	.15784	.00238	.00016	.00420	.00001
1400	.02906	1.3324	.66162	-------	.00756	.00002	.16902	.00032	.16146	-------	-------	-------	-------
r = 0.75 (31.65 percent fuel by weight)													
3879	20.41	------	0.48584	0.03359	0.06312	0.05332	0.03894	0.02255	0.17425	0.01957	0.05183	0.05336	0.00361
3800	16.74	1.1547	.49086	.03245	.06642	.05209	.04036	.02178	.17599	.01759	.04845	.05085	.00316
3600	9.924	1.1518	.50326	.02925	.07572	.04841	.04411	.01971	.18045	.01309	.03980	.04404	.00217
2900	1.260	1.1526	.54119	.01415	.11740	.02838	.05789	.01141	.19590	.00313	.01214	.01808	.00033
2400	.2803	1.1898	.55763	.00383	.14397	.01131	.06647	.00572	.20404	.00060	.00185	.00455	.00003
1600	.03442	1.2953	.56299	.00002	.15522	.00032	.07242	.00062	.20837	-------	-------	.00002	-------
r = 1.00 (38.45 percent fuel by weight)													
3789	20.41	------	0.42303	0.07383	0.10927	0.05009	0.01651	0.01498	0.20693	0.00880	0.06479	0.02877	0.00300
3700	16.15	1.1514	.42726	.07188	.11558	.04820	.01662	.01412	.20914	.00769	.06025	.02670	.00256
3500	9.273	1.1476	.43670	.06679	.13114	.04336	.01664	.01211	.21419	.00551	.04991	.02193	.00172
2900	1.399	1.1435	.46355	.04434	.18825	.02440	.01365	.00599	.22933	.00144	.02039	.00833	.00033
2400	.2579	1.1661	.48037	.02002	.23646	.00847	.00714	.00203	.23927	.00024	.00442	.00156	.00003
1700	.03247	1.2640	.48821	.00128	.26554	.00026	.00053	.00009	.24406	-------	.00003	.00001	-------
r = 1.25 (44.14 percent fuel by weight)													
3681	20.41	------	0.37042	0.12116	0.13761	0.03742	0.00602	0.00880	0.23145	0.00430	0.06690	0.01368	0.00224
3600	16.47	1.1527	.37335	.11986	.14383	.03526	.00571	.00806	.23347	.00372	.06253	.01230	.00191
3400	9.481	1.1507	.38048	.11631	.16001	.02945	.00476	.00624	.23846	.00250	.05160	.00896	.00124
2700	1.221	1.1739	.40084	.10548	.21298	.00779	.00074	.00111	.25305	.00029	.01665	.00095	.00012
2100	.2670	1.2525	.40659	.10695	.22689	.00043	.00001	.00003	.25712	.00001	.00197	.00001	-------
1200	.02192	1.3168	.40710	.10780	.22765	-------	-------	-------	.25745	-------	-------	-------	-------

TABLE IV - EQUILIBRIUM COMPOSITION IN COMBUSTION CHAMBER AND FOLLOWING AN ISENTROPIC EXPANSION TO ASSIGNED EXIT TEMPERATURES - Concluded

[Commercial fuel: 86.11 percent N_2H_4 and 13.89 percent $N_2H_4 \cdot H_2O$ by weight; oxidant: OF_2]

Temperature T (°K)	Pressure P (atm)	γ_s $\left(\frac{\partial \log P}{\partial \log \rho}\right)_S$	Equilibrium composition (mole fraction)										
			HF	H_2	H_2O	OH	O_2	NO	N_2	F	H	O	N
					r = 1.50 (48.97 percent fuel by weight)								
3551	20.41	------	0.32691	0.17309	0.15008	0.02401	0.00190	0.00461	0.24959	0.00206	0.06062	0.00565	0.00150
3500	17.95	1.1606	.32822	.17311	.15329	.02263	.00175	.00425	.25070	.00185	.05776	.00511	.00134
3200	8.256	1.1652	.33547	.17410	.17142	.01444	.00090	.00231	.25685	.00087	.04065	.00238	.00061
2500	1.430	1.2180	.34574	.18206	.19569	.00177	.00003	.00016	.26546	.00005	.00894	.00007	.00003
1800	.2758	1.2843	.34767	.18620	.19882	.00002	-------	-------	.26700	-------	.00029	-------	-------
1000	.02306	1.3360	.34773	.18636	.19886	-------	-------	-------	.26705	-------	-------	-------	-------
					r = 1.75 (53.12 percent fuel by weight)								
3404	20.41	------	0.29062	0.22529	0.15138	0.01380	0.00054	0.00221	0.26285	0.00095	0.04939	0.00207	0.00090
3300	15.95	1.1747	.29244	.22706	.15582	.01155	.00041	.00175	.26464	.00072	.04341	.00154	.00068
3100	9.917	1.1824	.29553	.23085	.16325	.00763	.00021	.00102	.26767	.00039	.03231	.00077	.00036
2300	1.599	1.2490	.30189	.24399	.17616	.00038	-------	.00003	.27376	.00001	.00377	.00001	.00001
1500	.2258	1.3052	.30253	.24615	.17695	-------	-------	-------	.27435	-------	.00002	-------	-------
900	.02830	1.3472	.30253	.24616	.17695	-------	-------	-------	.27435	-------	-------	-------	-------
					r = 2.00 (56.72 percent fuel by weight)								
3249	20.41	------	0.26016	0.27359	0.14650	0.00740	0.00014	0.00100	0.27263	0.00042	0.03696	0.00070	0.00049
3200	18.28	1.1882	.26074	.27480	.14783	.00666	.00012	.00088	.27328	.00036	.03432	.00059	.00042
2900	9.411	1.2047	.26367	.28194	.15420	.00306	.00003	.00033	.27652	.00013	.01983	.00016	.00014
2100	1.650	1.2716	.26680	.29239	.15953	.00007	-------	-------	.27990	-------	.00131	-------	-------
1300	.2034	1.3200	.26698	.29321	.15972	-------	-------	-------	.28009	-------	-------	-------	-------
800	.02990	1.3577	.26698	.29321	.15972	-------	-------	-------	.28009	-------	-------	-------	-------
					r = 2.50 (62.68 percent fuel by weight)								
2947	20.41	------	0.21242	0.35140	0.13080	0.00191	0.00001	0.00019	0.28552	0.00008	0.01748	0.00007	0.00012
2900	18.55	1.2195	.21265	.35243	.13124	.00166	.00001	.00016	.28584	.00006	.01579	.00006	.00010
2600	10.07	1.2410	.21377	.35778	.13319	.00056	-------	.00004	.28739	.00002	.00721	.00001	.00002
1700	1.374	1.3011	.21463	.36243	.13433	-------	-------	-------	.28854	-------	.00008	-------	-------
1200	.3218	1.3305	.21463	.36248	.13433	-------	-------	-------	.28856	-------	-------	-------	-------
800	.06645	1.3610	.21463	.36248	.13433	-------	-------	-------	.28856	-------	-------	-------	-------

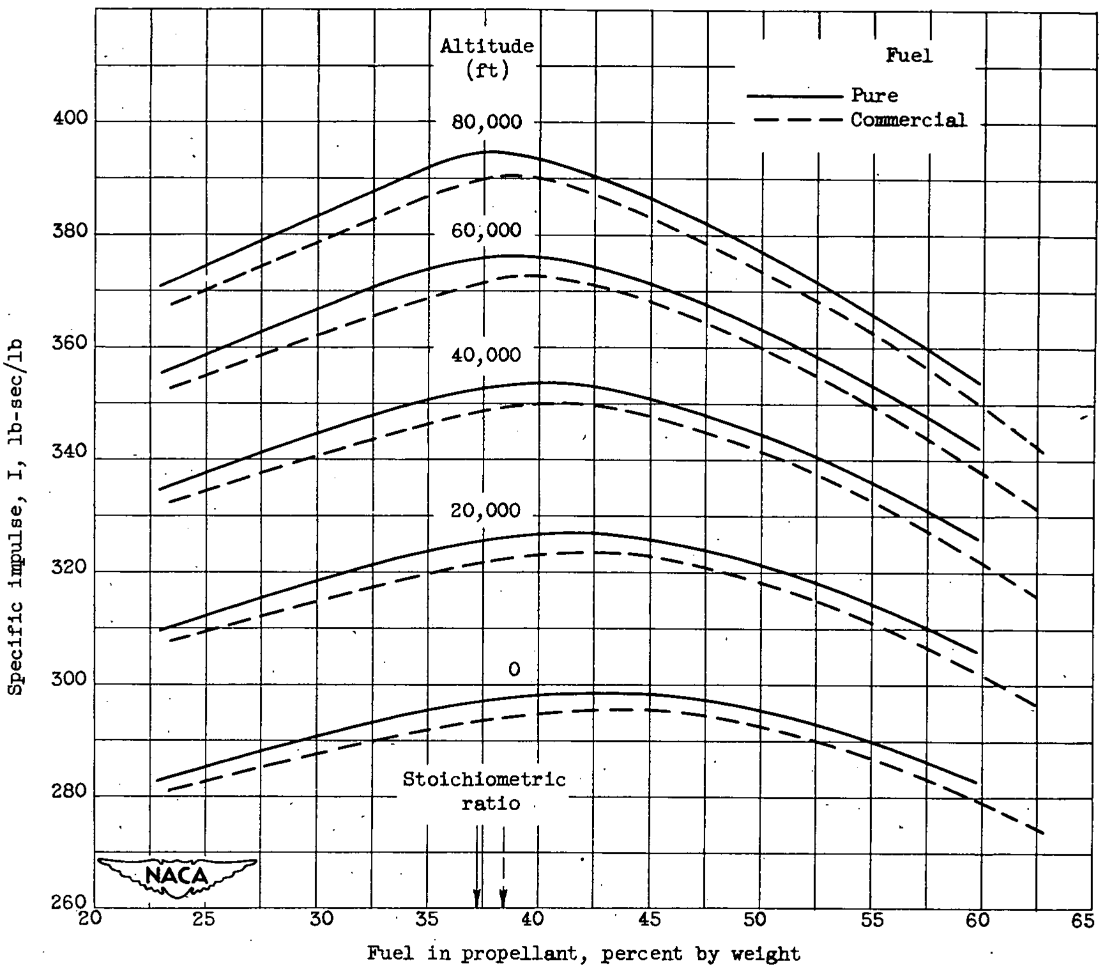


Figure 1. - Theoretical specific impulse of hydrazine with liquid oxygen bifluoride. Pure fuel: 100 percent hydrazine; commercial fuel: 86.11 percent hydrazine, 13.89 percent hydrazine hydrate by weight; isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

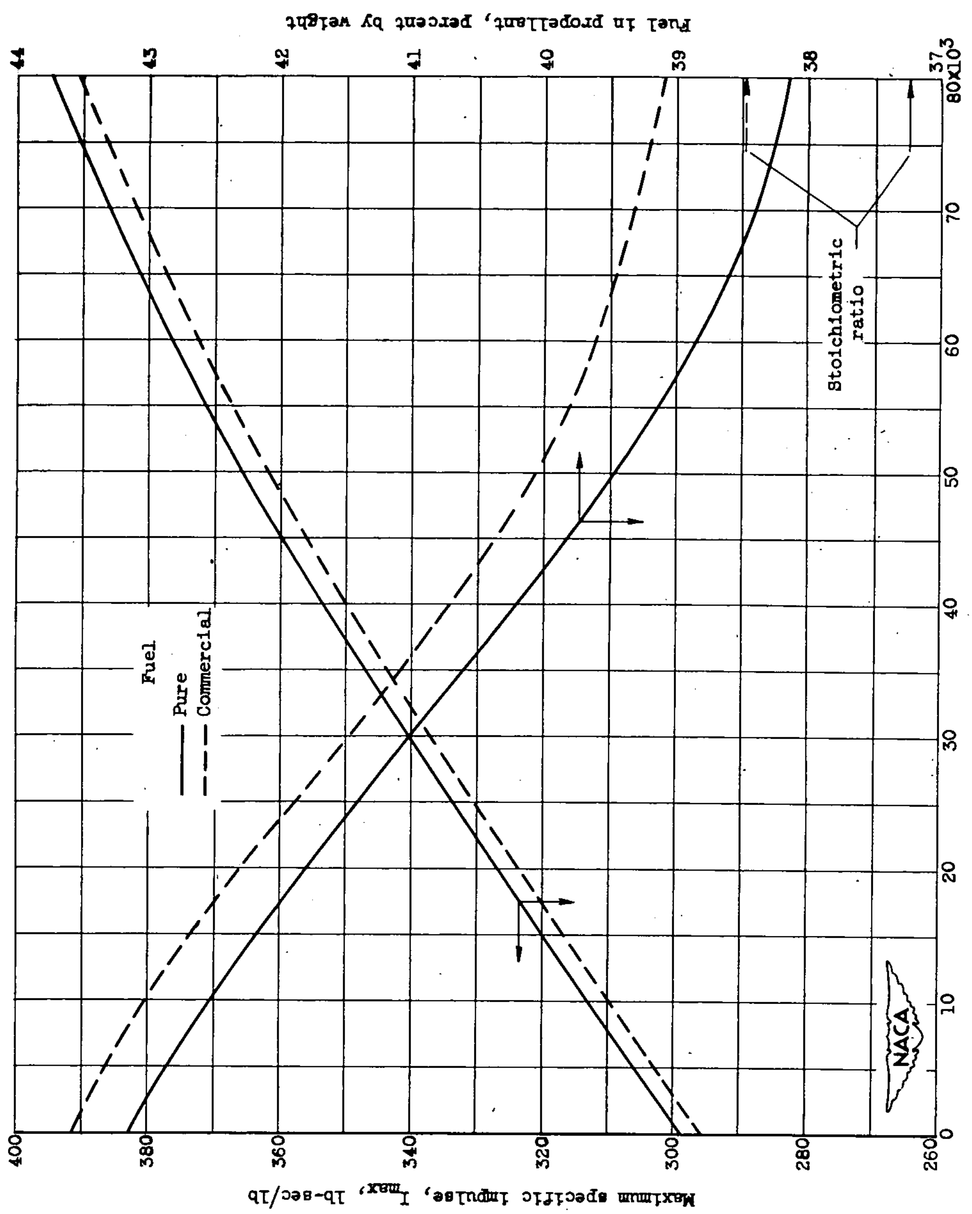


Figure 2. - Maximum theoretical specific impulse and corresponding weight percent of fuel in propellant of hydrazine with liquid oxygen bifluoride. Pure fuel: 100 percent hydrazine; commercial fuel: 86.11 percent hydrazine, 13.89 percent hydrazine hydrate by weight; isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

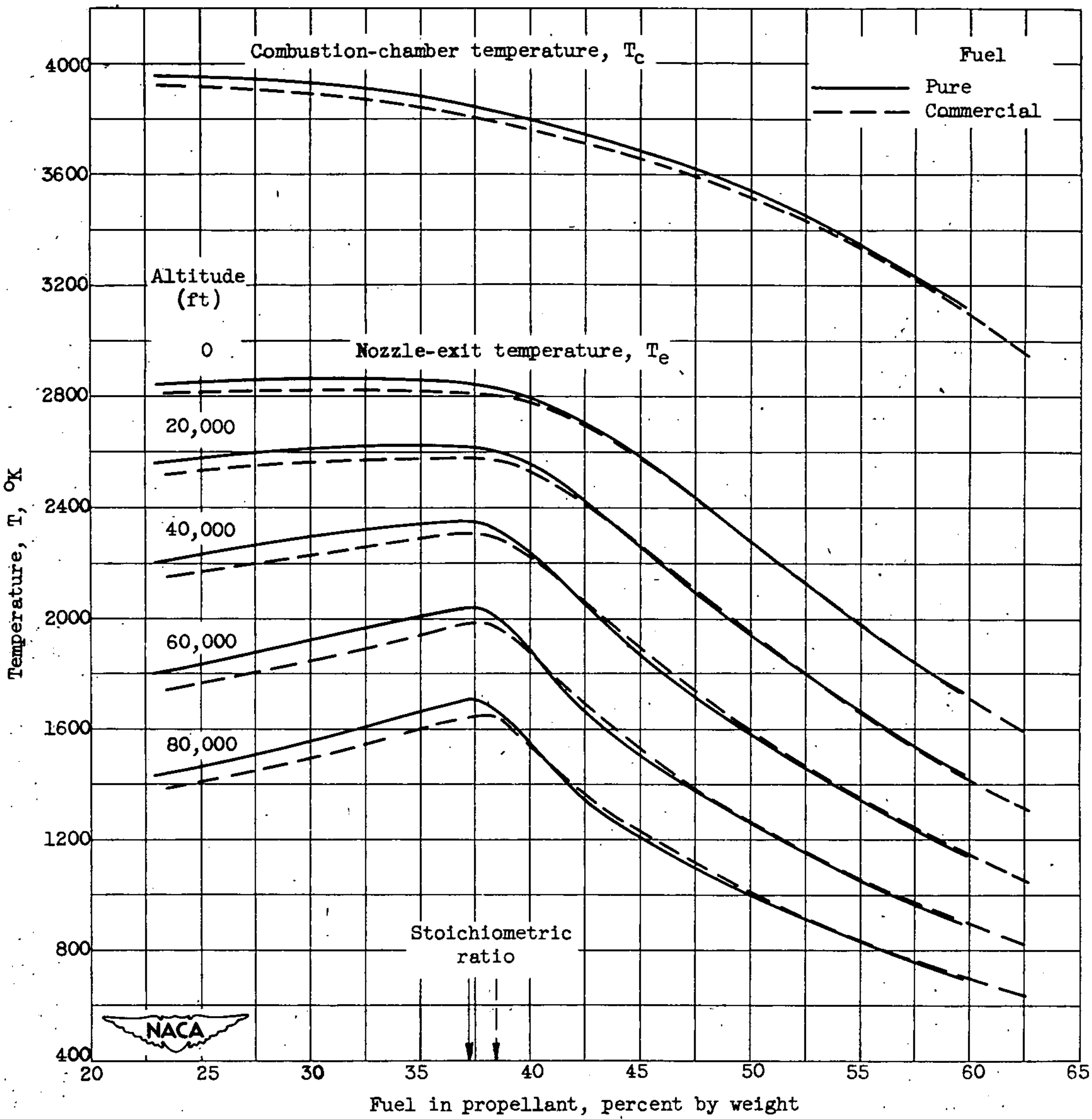


Figure 3. - Theoretical combustion-chamber temperature and nozzle-exit temperature of hydrazine with liquid oxygen bifluoride. Pure fuel: 100 percent hydrazine; commercial fuel: 86.11 percent hydrazine, 13.89 percent hydrazine hydrate by weight; isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

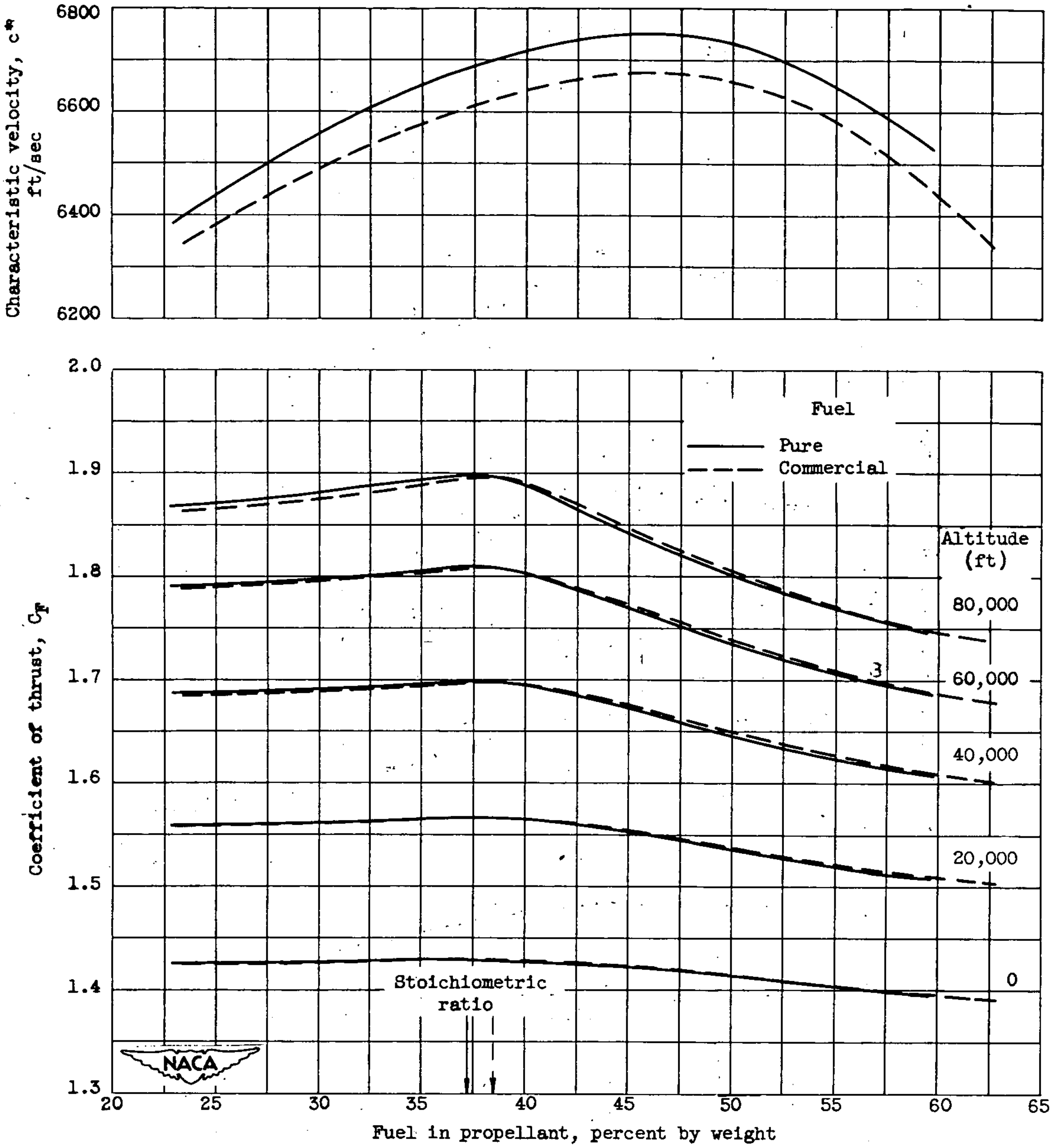


Figure 4. - Theoretical characteristic velocity and coefficient of thrust of hydrazine with liquid oxygen bifluoride. Pure fuel: 100 percent hydrazine; commercial fuel: 86.11 percent hydrazine, 13.89 percent hydrazine hydrate by weight; isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

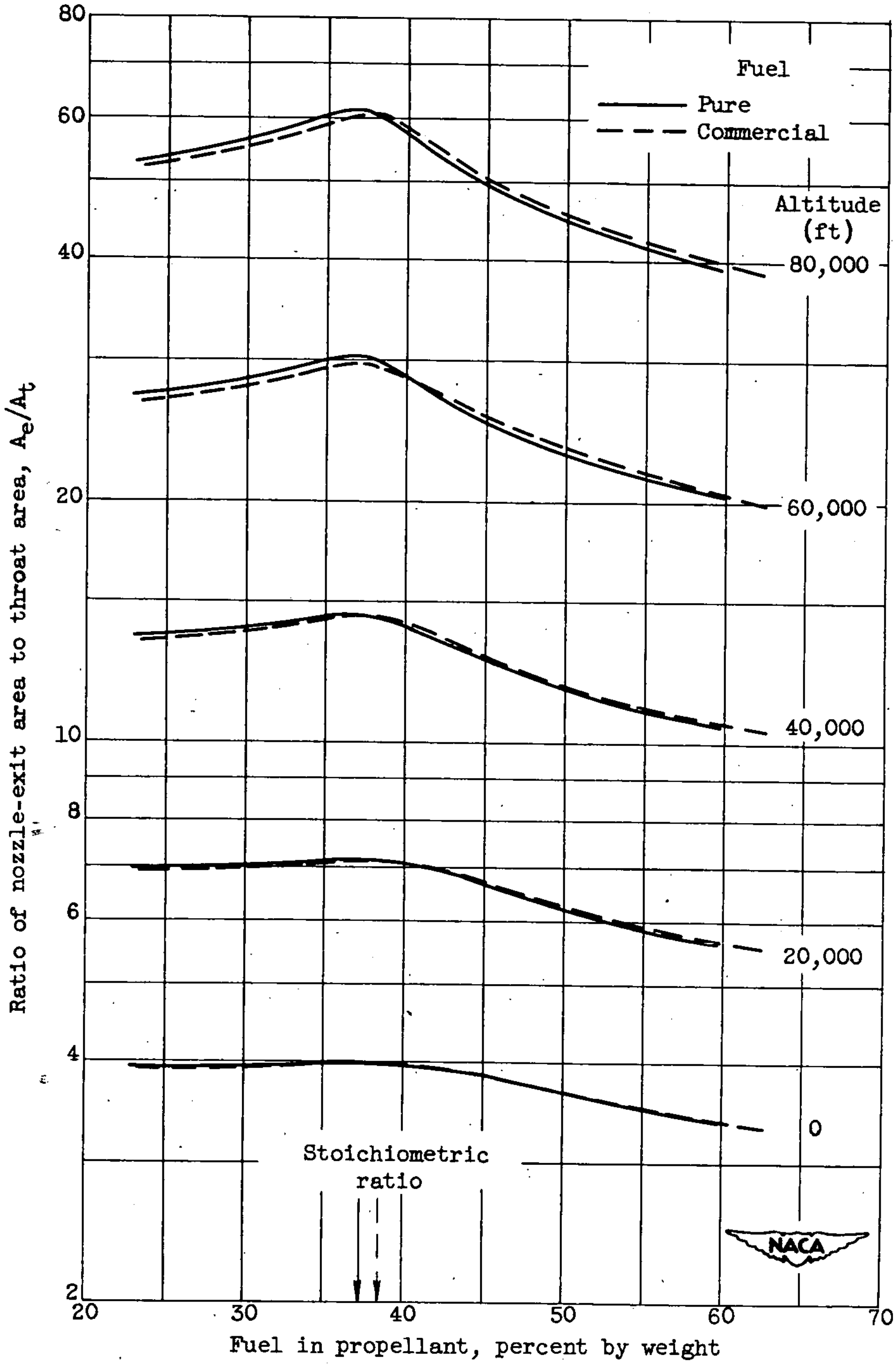
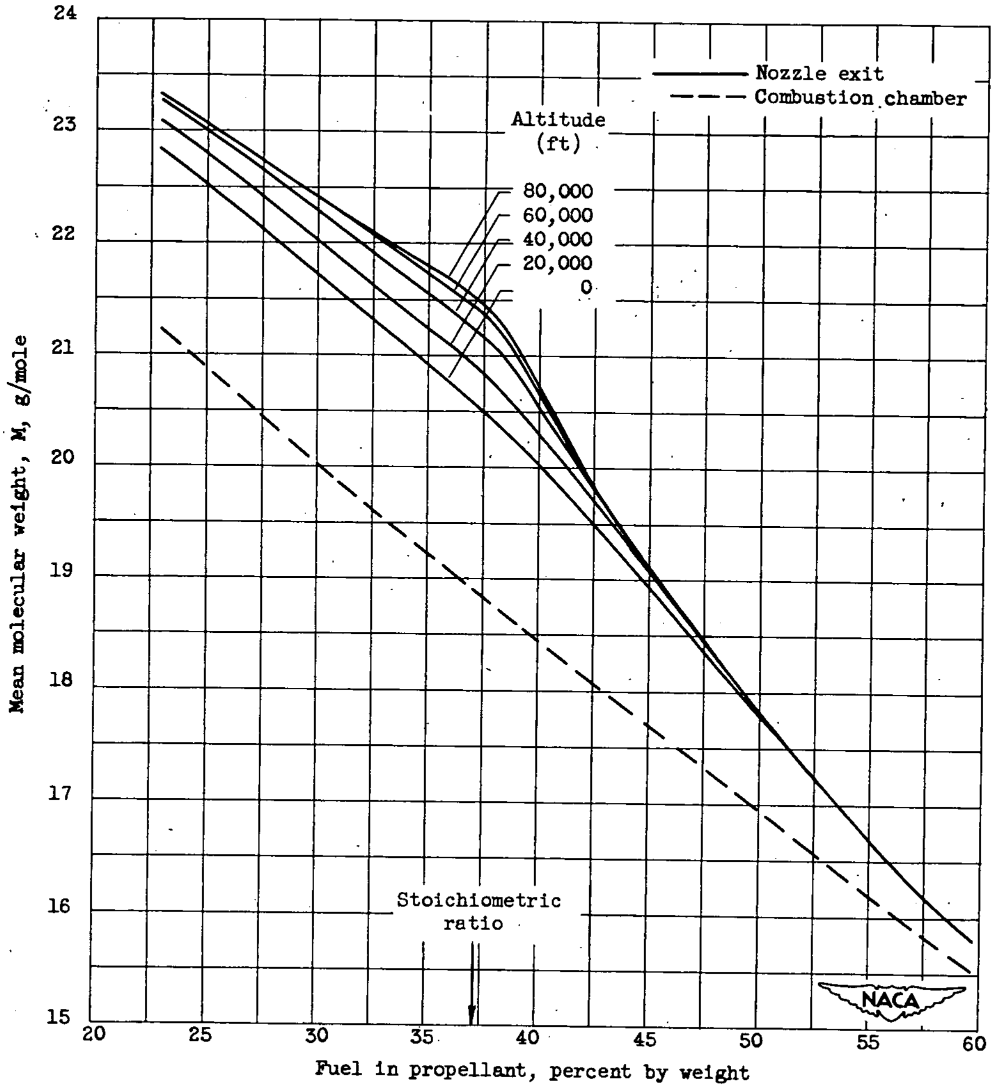
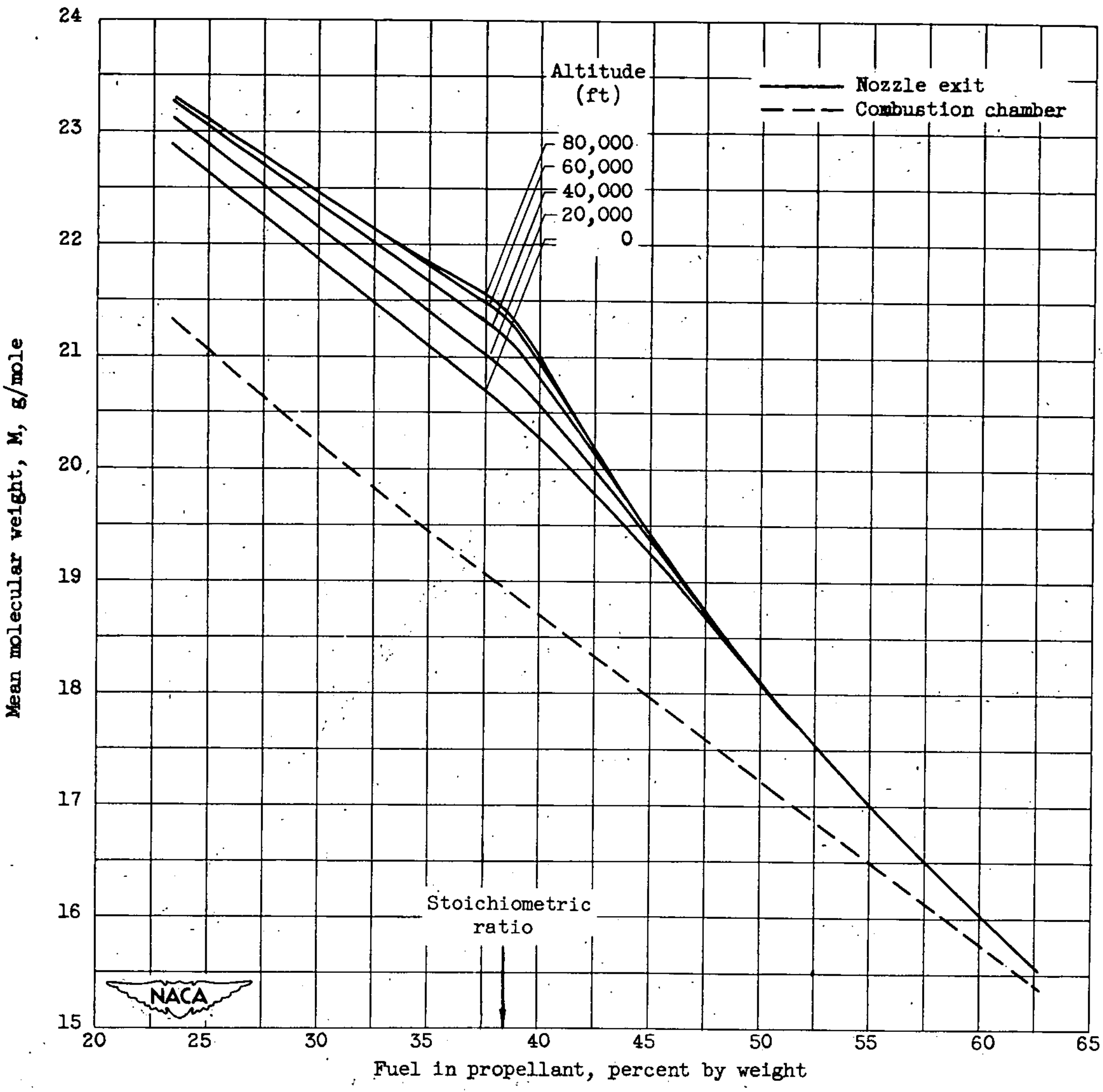


Figure 5. - Theoretical ratios of nozzle-exit area to throat area of hydrazine with liquid oxygen bifluoride. Pure fuel: 100 percent hydrazine; commercial fuel: 86.11 percent hydrazine, 13.89 percent hydrazine hydrate by weight; isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.



(a) Pure fuel: 100 percent hydrazine.

Figure 6. - Theoretical mean molecular weight of hydrazine with liquid oxygen bifluoride in combustion chamber and at nozzle exit. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.



(b) Commercial fuel: 86.11 percent hydrazine, 13.89 percent hydrazine hydrate by weight.

Figure 6. - Concluded. Theoretical mean molecular weight of hydrazine with liquid oxygen bifluoride in combustion chamber and at nozzle exit. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

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